Diffuse neutral hydrogen in the Local Universe

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Summary and Future Notes

8.1 Summary

In this thesis we have tried to improve our understanding of the distribution of neutral hydrogen in the Local Universe.

8.1.1 Introduction

Numerical simulations predict that galaxies and clusters in the Local Volume are connected by extended diffuse filaments of gas. Although most of this gas is ionised, the peaks of this Cosmic Web should be detectable in H I 21cm emission at column densities that probe those of Lyman Limit systems.

These low column densities are a very interesting region to explore. Much is unknown about feedback processes and the accretion of gas onto galaxies. Furthermore, the direct detection of the Cosmic Web can confirm the cosmological model we currently accept and possibly solve the missing baryon problem.

Currently, most H I observations are limited to a brightness sensitivity of $N_{HI} \sim 10^{19}$ cm^{-2}. This is the column density where the H I "edge" of galaxies is, and is approximately the column density below which the neutral fractions drops rapidly, as the effect of self-shielding decreases. This is a physical constraint that limits the detection of H I at low column densities. Detecting column densities significantly below $N_{HI} \sim 10^{19}$ cm^{-2} in H I emission requires long integration times.

In the near future many scientifically interesting results will emerge from radio telescopes that are currently under development. Several examples are ASKAP in Australia, MeerKAT in South Africa and APERTIF in the Netherlands; all functioning as pathfinders for the SKA. Hopefully these facilities will provide many answers regarding galaxy formation and the distribution of neutral hydrogen on large scales.

While these telescopes are still in the design phase, it is essential to perform preliminary work to improve our knowledge using existing facilities. When pushing the limits of current telescopes, a better understanding can be achieved of possible results and complications. This is necessary to set realistic science goals, and to be well prepared when the future facilities are delivered.

As telescopes will always be limited by sensitivity at a certain point, observations alone cannot provide all possible information about the distribution of gas and matter, and cannot answer all the questions. Simulations are a very valuable tool to make predictions for observations that probe different cosmological models.

8.1.2 Individual chapters

We will briefly summarise the most important results from each individual chapter.

Chapter 2: The Standing Wave Phenomenon in Radio Telescopes: Frequency Modulation of the WSRT Primary Beam.

- Inadequacies in the knowledge of the primary beam response of telescopes form a limit to the image fidelity of deep observations.
- The WSRT has been used to obtain Holographic observations of a bright compact source (3C147) sampling angular scales between 5 arcmin and 11 degrees
- A robust empirical beam model was detemined in all polarization products (XX, XY, YX and YY) and at frequencies between 1322 and 1457 MHz with 1 MHz resolution.
- Substantial departures from axi-symmetry are apparent in the main-lobe as well as systematic differences between the polarization properties.
- Many beam properties are modulated at the 5 to 10% level with changing frequency. These semi-sinusoidsal modulations have a basic period of about 17 MHz, consistent with the natural standing wave period of a 8.75 m focal distance.

Chapter 3: The simulated H I *sky at low redshift*

- We study the distribution of neutral hydrogen and its 21-cm emission properties in a cosmological hydrodynamic simulation, to gain more insight into the distribution of H I below $N_{HI} \sim 10^{19}$ cm^2
- The neutral component of the Cosmic web is extracted by determining the neutral fraction of SPH particles, including a post-processing correction for self-shielding based on the thermal pressure and taking into account molecular hydrogen.
- The simulated H I distribution robustly describes the full column density range between $N_{HI} \sim 10^{14}$ and $N_{HI} \sim 10^{21}$ cm^2 .
- The statistical properties of the reconstructed maps have been compared with available statistics from observations. There is good correspondence when looking at univeral H I density, the two-point correlation function and the H I mass function.

- Reconstructed H I maps can be used to simulate observations by adding noise and accounting for the sensitivity of specific telescopes.

Chapter 4: The WSRT Virgo H I *Filament Survey I: Total Power Data*

- The galaxy filament connecting the Virgo Cluster with the Local group has been mosaiced by the Westerbork Synthesis Radio Telescope.
- By using the 14 antennae of the array in total power mode, very high brightness sensitivity is achieved at the expense of poor angular resolution.
- Almost all galaxies catalogued in the HIPASS database can be confirmed and 20 new candidate detections are identified of which most do not have an optical counterpart.
- As these objects have not been detected before at higher column densities, they are possibly very extended and diffuse.
- When these detections can be confirmed in other surveys, the constitute a whole sample of objects of relavance to the Cosmic Web.

Chapter 5: Diffuse neutral hydrogen in the H I *Parkes All Sky Survey*

- A subset of the original HIPASS observations have been re-processed, covering the WVFS survey region.
- The re-processed data has a slightly improved sensitivity and significantly improved noise characteristics, compared to the original HIPASS product.
- In the re-processed data we have identified 27 additional sources, of which 14 are completely new H I detections and 8 do not have an optical counterpart.
- From the visiually inspected moment maps of the environment of H I galaxies, another 10 tentative companion structures have been revealed.

Chapter 6: The WSRT Virgo H I *Filament Survey II: Cross Correlation Data*

- The galaxy filament connecting the Virgo Cluster with the Local group has been mosaiced by the Westerbork Synthesis Radio Telescope.
- By observing at extreme hour angles, a filled aperture in projection has been simulated of 300×25 meter extent. This permits a high brightness sensitivity that is comparable to a single dish telescope, combined with the excellent bandpass calibration of an interferometer.
- A total of 193 H I objects have been detected. Although not all sources in the HIPASS catalogue are detected by an automatic source finder, we detect 16 new H I features

Chapter 7: H I *surveys: Data comparison.*

- The data of the three H I surveys described in this thesis are compared.
- All new detections in either of the three surveys are confirmed and new H I detections are sought that emerge from the direct data comparison.
- We confirm 32 new H I detections, of which 16 do not have an obvious optical counterpart.
- All H I detections without optical counterparts appear to be extended, as the flux in the low resolution data is higher than in the WVFS cross-correlation data.
- The apparently isolated H I sources have an H I mass less than $\sim 10^9\ M_\odot$ and column density below $N_{HI} \sim 10^{19}$ cm^{-2} in the data with the highest angular resolution.
- As a general trend more flux is detected in the two single-dish data products, indicating that there is a significant amount of diffuse neutral hydrogen in the extended environment of galaxies.
- We have detected a sample of H I objects with kinetic temperatures of a few times $\sim 10^4$ K, that are most likely tracers of the dense and cool regions of the local Cosmic Web.

8.1.3 The emerging picture

We have reconstructed the distribution of neutral hydrogen from a hydrodynamic simulation, which describes the full column density range from the diffuse Ly-α forest to dense galaxies. Three different H I surveys have been used to search for and confirm diffuse detections of neutral hydrogen.

Before considering doing very deep H I observations, a good understanding is required of sensitivity and the technical limitations and capabilities of telescopes. Although interferometric observations can achieve very good flux sensitivities, the brightness sensitivities are very limited due to the relative small synthesised beam. Here lies the great benefit of single-dish telescopes; since they have a larger beam size, they typically have a better brightness sensitivity, at the cost of angular resolution.

Both simulations and observations confirm that there is a significant amount of baryonic matter in the Inter Galactic Medium and extended neutral hydrogen can be found when exploring Lyman limit system column densities between 10^{16} and 10^{19} cm^{-2}.

The angular resolution of our observations is not sufficient to resolve the transition from high to low column densities. It appears that the detected Cosmic Web features have a relative dense core which is unresolved in the WVFS cross-correlation data ($\sim$ 15 kpc). Although the observed emission does not exceed $N_{HI} \sim 10^{19}$ cm^{-2} the peak column densities might be slightly higher since the emission is diluted in the beam. Outside this dense core, there is extended neutral hydrogen up to a radius of $\sim$ 100 kpc.

Detecting the dense and relative cool components of the local Cosmic Web in neutral hydrogen is possible, but requires a major effort since very deep observations are required.

We have explored column densities that probe the Lyman limit regime and can confirm a number of diffuse detections in different surveys.

Based on this work, there are still many Cosmic Web features that remain to be detected, assuming that they are uniformly distributed over the sky. Reaching lower column densities than the ones described in this thesis is not really feasible for large regions of the sky with current instruments. Data of the HIPASS and ALFALFA surveys do however offer an excellent opportunity to search for diffuse H I. The complete HIPASS survey can be reprocessed in a similar or possibly even improved fashion as described in this thesis. Steps are already underway for a second generation HIPASS product. A dedicated search with an improved searching algorithm should result in many new H I detections of which a significant fraction would not have an optical counterpart. The ALFALFA survey has an excellent flux sensitivity, although the brightness sensitivity is not as good due to the small beam. Especially where the two surveys overlap, diffuse detections can be confirmed and the denser regions can possibly be resolved with the ALFALFA data.

8.2 Future notes

In this thesis we have made an effort to detect very diffuse neutral hydrogen emission. Although this has resulted in a number of detections, we have also faced many complications and difficulties, most of which have not been mentioned in detail. The technical capabilities of future telescopes and surveys will hopefully be significantly improved over the capabilities we have today. Nevertheless we will mention a few points that might be relevant for future work as well.

8.2.1 Source Finders

The manual searching procedures that have been used in the different surveys were not favoured, but were deemed necessary as the available searching algorithms were not sufficiently capable.

With the development of the SKA and the many SKA-pathfinders a general trend is emerging for immense data sets. All these future telescopes can map the sky significantly faster or deeper, compared to the current generation of telescopes. In the near future, all-sky surveys will be undertaken, but not only to expand the database of known sources or to improve the statistics. The true value of future telescopes in general (not only radio telescopes) is to explore science questions that could not be investigated before, because of inadequate instrumentation. Examples are detections of H I emission at high redshift, transients or dark galaxies. What many of these topics have in common is a general belief or expectation regarding what will be discovered. The actual existence or physical properties have yet to be proven. The common challenge that these unexplored topics presents is that they are very faint and/or very hard to detect. Here is a serious challenge for source-finders that will be critical to address. They should not only be sensitive to well defined objects but particularly to features that are almost hidden in the noise.

8.2.2 Standing Waves

When doing very deep observations, a significant effort is required to reach the thermal noise of the telescope and achieve the highest sensitivity. When looking for diffuse structures, single dish telescopes are very valuable, because of their excellent brightness sensitivity. At some level, those sensitivities are however limited by a hardware effect in the form of mutli-path interference effects involving the receiver and dish of the telescope. This has been discussed in detail for the WSRT, but plays a role for all radio telescopes as has been shown for the Parkes telescope in this chapter.

Diffuse neutral hydrogen can be detected with current instrumentation, but it is extremely challenging as it is even extended on the scale of total power beams. Current single dish telescopes have the potential to map this diffuse emission with long integrations. However, to be successful and to experiment with the necessary spatial smoothings a serious effort has to be undertaken to decrease the effect of standing-waves.

8.2.3 Follow up H I observations

In this thesis we have identified a list of objects that are tantalizing detections of the Cosmic Web. All these intergalactic features appear to be very extended with very low column densities. A logical step is to do deep follow-up observations (preferably with an interferometer) at higher resolution to be able to resolve and image the denser cores of these filaments. This would provide information about the detailed kinematics and show the decline from high to low column densities, at least as far as the sensitivity of the observations allow. This is however only one aspect of the complete picture. Many objects appeared to be larger in angular diameter than the beam of the Parkes telescope. Deep observations at the moderate resolution of large single-dish telescopes that reach the column density sensitivity of the WVFS total-power data can show the full extent of these intergalactic gas clouds. To achieve this goal, the sensitivity of the HIPASS observations will have to be improved by about an order of magnitude, which means that the integration times will need to be increased by a factor of 100. Accomplishing these long integration times on large regions of the sky may not be realistic until much larger instantaneous fields-of-view become available.

8.2.4 Next generation radio telescopes

The future of the search for diffuse neutral hydrogen is in the next generation of radio interferometers. By using new techniques, some of these telescopes can map the sky significantly faster. Very recently, several science projects have been defined that will be taken to the design study phase for ASKAP. The most relevant to this thesis is WALLABY (Widefield ASKAP L-band Legacy All-sky Blind surveY), which will undertake an all sky H I survey of the Local Universe. The proposed sensitivity of this survey is 0.7 mJy beam^{-1} in a 30" beam over 0.1 MHz after integrating for 8 hours per pointing. The column density sensitivity that can be achieved is $N_{HI} \sim 1.7 \times 10^{19}$ cm^{-2} which is very impressive for an all sky survey at this resolution. When using a different weighting scheme and gridding the data to an angular resolution of 180", a column density sensitivity of $N_{HI} \sim 1.8 \times 10^{18}$ cm^{-2} should be achievable. This is very comparable to the brightness sensitivity of the WVFS total power data.

As WALLABY is an all sky survey, it will find many Cosmic Web filaments, where the densest cores can immediately be resolved. The sensitivity is still not sufficient to map the full extent and to image the transition from high to low column densities. The size of one ASKAP pointing is 30 square degrees, which is a perfect size to map an object in the nearby universe and its extended environment. The column density sensitivity can be improved to a few times 10^{17} with relative little effort for a selected pointings.

The true breakthrough regarding observing the Cosmic Web in neutral hydrogen will come with the SKA. Although the technical parameters have still to be defined, we assume that the sensitivity will be about an order of magnitude improved over ASKAP. Achieving a column density sensitivity of $10^{16} - 10^{17}$ cm^{-2} at a resolution of ~ 3 arcmin over a large region of the sky will finally be a realistic possibility.